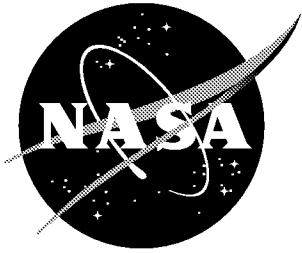


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Cryogenic Pressure Calibrator for Wide Temperature Electronically Scanned (ESP) Pressure Modules

*Nettie D. Faulcon
Langley Research Center, Hampton, Virginia*

October 2001

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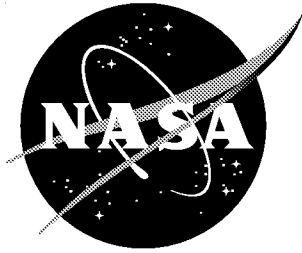
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*Nettie D. Faulcon
Langley Research Center, Hampton, Virginia*

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Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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CRYOGENIC PRESSURE CALIBRATOR FOR WIDE TEMPERATURE ELECTRONICALLY SCANNED (ESP) PRESSURE MODULES

ABSTRACT

Electronically scanned pressure modules have been developed that can operate in ambient and in cryogenic environments, particularly Langley's National Transonic Facility (NTF). Because they can operate directly in a cryogenic environment, their use eliminates many of the operational problems associated with using conventional modules at low temperatures. To ensure the accuracy of these new instruments, calibration was conducted in a laboratory simulating the environmental conditions of NTF. This paper discusses the calibration process by means of the simulation laboratory, the system inputs and outputs and the analysis of the calibration data. Calibration results of module M4, a wide temperature ESP module with 16 ports and a pressure range of ± 4 psid are given.

INTRODUCTION

Wind tunnels of different sizes and environmental conditions are used to test the design and concept of all aerospace vehicles before they are committed to flight. One of Langley Research Center's most advanced facilities is the National Transonic Facility (NTF), a high pressure, cryogenic, closed-circuit wind tunnel that has the unique capability of using either air or cryogenic nitrogen as test gases. Air is used as the test gas in the ambient temperature mode and in the variable temperature cryogenic mode, nitrogen is the test gas.

To analyze a complex aerodynamic model a variety of parameters must be measured. Among the desired properties to be measured is the pressure at different orifices on the models. For over two decades, conventional electronically scanned pressure (ESP) modules have been used for this purpose because of their high accuracy, low cost-per-channel, small size, and ease of use. In NTF, ESP systems provide high accuracy measurement of model and facility pressures at rates of 500 samples per second. However, at cryogenic temperatures, their use presents obstacles that contribute to the overall expense of testing and the loss of data quality. One obstacle is the need for thermal protection of the module because of charge carrier freeze-out (ref. 1, 2). Another major obstacle is the requirement that a test be interrupted periodically for

on-line calibration, consuming as much as 25% of the total test time, distracting from wind tunnel productivity. In NTF, there was a mammoth need to have an instrument that would eliminate the operational problems associated with using conventional ESP modules. To this end, wide temperature ESP modules have been produced.

As with all instruments, the wide temperature modules require high accuracy calibration, but this calibration, however, must be made in an environment meeting the specifications required for testing in the National Transonic Facility. Therefore, in order to calibrate these modules, a laboratory simulating the NTF environment was created. This environment was created using vaporized liquid nitrogen, a high-pressure chamber with heater coils, associated electronic instrumentation and various reference and calibration pressures. The aforementioned wide temperature modules have been successfully calibrated in this laboratory.

ESP TECHNOLOGY

Conventional Modules

Electronically scanned modules are differential pressure measurement units consisting of an array of silicon pressure sensors which are electronically multiplexed at rates of 20,000 Hz through an on board multiplexer and instrumentation amplifier. Found today in widespread practice throughout the world to measure surface pressure on models and walls of wind tunnels, these state-of-the-art ESP modules typically contain 16 - 64 measurement channels connected to pressure ports through small diameter tubing. Although they have served the aerospace industry well for testing near ambient conditions, their use in cryogenic environments poses practical problems that add to the expense of testing and to the loss of data quality. One major problem is the need for thermal protection because pressure dice and electronic components of the modules fail to work properly when temperature is lowered. Traditionally the way to overcome this difficulty has been to enclose each module in a heater box before placing in a model to be tested. In addition to being time consuming and expensive, this procedure also reduces available space in the model for scanners, requires careful temperature control and the ability to maintain a uniform temperature throughout the contained scanner is uncertain.

The accuracy of the modules is maintained through periodic on-line re-zero and calibration via of a built in, pneumatically driven sliding valve that requires two pneumatic lines for service as well as one for the applied calibration pressure (ref. 2). The frequency of calibration is dependent on ambient temperature changes and electrical drift of the transducers with time. The test interruptions, nevertheless, can consume as much as 25% of the total test time.

Wide Temperature Modules

Langley developed wide temperature ESP modules were produced to eliminate the problems associated with conventional ESP modules when used in a cryogenic environment (ref. 4). Very stable with respect to zero drift, the measurement uncertainty of these ESP modules is less than 0.1 % F.S.O. over the entire temperature range. Modules range from 16 to 64 ports, with pressure ranges from ± 4 to ± 45 psid and operate from 75° to -175° C without the use of a heater box to provide protection from the cryogenic environment. Each silicon pressure die contains a temperature sensor, which, together with a reference pressure provide continuous on-line calibration. The offset and sensitivity coefficients, obtained from careful laboratory calibration, are preloaded into the tunnel's data acquisition system, thus eliminating the need for in-test pressure calibration. Service air needed for calibration is also eliminated because the sliding valve found in conventional modules and the associated service pressure and calibration pressure lines are eliminated. Moreover, the stability of the modules ensures that the calibration is good for up to an estimated 6 months. With the added benefits of ease of installation and the easy replacement of defective silicon die, the wide temperature ESP modules present a significant reduction in overall cost and test cycle time.

CALIBRATION SYSTEM

Newly developed modules are calibrated in a high-pressure environment in the National Transonic Facility Simulation Laboratory. The laboratory consists of the following five subsystems as shown in Figure 1.

1. Cryogenic High Pressure Chamber
2. Measurement and Control of Internal Chamber Temperature
3. Cryogenic Supply Line
4. Pressure Supply for Reference and Calibration

5. Data Acquisition System

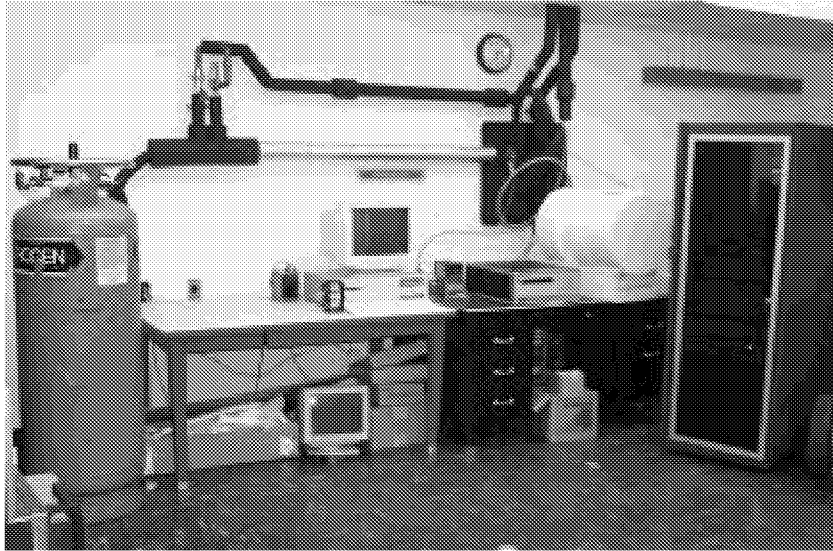


Figure 1. National Transonic Facility Simulation Laboratory

The calibration instruments used in these subsystems are a Pressure Systems, Inc. 8400 System, a West 5010 temperature controller, and a Mensor PCS 400 pressure controller. The accuracy of each instrument is given in Table 1.

DEVICE	MEASUREMENT	ACCURACY
PSI 8400 System	Air Pressure Scanning	$\pm 0.1\%$ F.S.
	High Pressure Accuracy	$\pm 0.02\%$ F.S.
	Pressure Calibration	$\pm 0.02\%$ F.S.
Mensor PCS 400	Reference Pressure Calibration	$\pm 0.025\%$ F.S. (including linearity, hysteresis , repeatability, and temperature after zeroing at the operating temperature)
West 5010	Thermocouple Input	$\pm 0.1\%$ of Span.

F.S. = Full Scale

Table 1. Accuracy of Calibration Instruments

Cryogenic High Pressure Chamber

The high pressure chamber is rated for reference pressures as high as eight atmospheres and temperatures as low as -175°C , thus allowing for accurate simulation of conditions encountered in the National Transonic Facility (NTF). The chamber, constructed with scheduled 40-seamless steel, is 60.96 centimeters (24 inches) long and has an internal diameter of 20.32 centimeters (8 inches). The ends of the chamber are sealed with two 20.32 (8 inches) flanges. On the back flange there are several feedthroughs used for the passage of thermocouple wires used for temperature measurement and for instrumentation wires that supply power voltage for the amplifier, multiplexes and constant current for RTD's on the ESP modules silicon chips. Copper tubing and gas lines also enter the chamber through the back flange.

Inside the chamber, a four-inch diameter copper cylinder block provides for heating and cooling of the module by transmitting heat between the module and the external heating and cooling sources. On one side of the block, along its entire length, is a rectangular shape cutout in which the module sits. Two rectangular copper pieces with passageways drilled along their lengths fit on each side of the module and are used as heat exchangers for gas used for calibration and chamber pressurization. The gas flows through the passageways aiding in equalizing the temperature of the incoming gas to that of the internal chamber. Copper tubing is wound over the entire circumference of the block from one end to the other. Liquid nitrogen flows through this tubing and cools the copper block. Minco Thermofoil heaters are pasted over the tubing providing heat to the block. To improve the heat transfer, 120 Series thermal compound is used to fill the air gap between the tubing and the outer surface of the copper block. The same thermal compound also provides a light bond and increases the heat transfer between the outer surface of the module and the surface of the copper block cutout in which the module sits.

Insulation material (Melamine) is fitted along the inner surface of the chamber, including the front and rear flanges. This insulation helps to reduce the heat transfer between the copper block and the inner walls of the chamber, thus allowing for the module to attain a lower total temperature. Insulation is also fitted over the entire outer surface of the chamber, reducing the heat flow between the chamber and the outside environment. Figure 2 shows the inside of the chamber viewed from the front and module M4 with associated tubing and wiring.

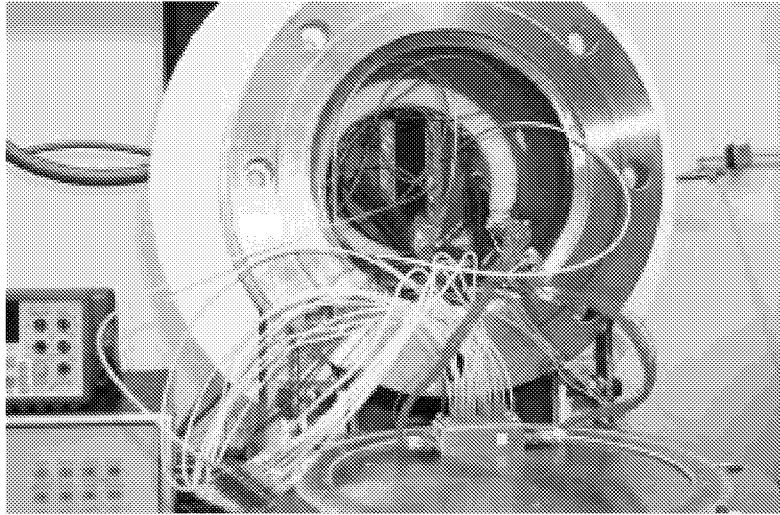


Figure 2. Wide Temperature Module and Frontal View of Inside of Calibration Chamber

Measurement and Control of Chamber Temperature

Temperature measurement inside the chamber is taken from within the copper block near the module, which ensures that calibration will be made at the desired set temperatures. Two CS02410 solid state relays located in a “cooling/heating” box and a West 5010 Temperature controller are used to regulate the temperatures. One solid state relay is used to control the solenoid valve that controls the liquid nitrogen flow (cooling) and the other is used to control the Minco Thermofoil heaters (heating). Connections from these two relays are made to the WEST 5010 Temperature controller, which is a single loop industrial controller with one universal input and two universal outputs located at the rear of its housing. Connected to the controller input is a T-type thermocouple that supplies temperature measurement near the module. The first output is connected to the relay controlling the heat, while the second is connected to the relay controlling the cooling. The temperature is set with the West controller and maintained by the two relays.

Calibration Supply for Cooling

Cooling of the chamber is accomplished using liquid nitrogen supplied to the chamber through an ASCO 40-psi solenoid valve from a liquid nitrogen Dewar fitted with a 50-psi relief valve. A 105-psi rupture disk and a 75-psi relief valve are attached to three-fourth inch supply piping ahead of the solenoid valve. Liquid nitrogen flows from the Dewar, through the solenoid valve and into the copper coils inside

the chamber. Liquid nitrogen exits the chamber and is vented into the atmosphere through a conventional piping system. A Dewar of 270 L or more will last the full time of calibration.

Pressure Supply for Calibration and Reference

Because it does not liquefy at low temperatures, helium is presently used as the supply gas for calibration and reference pressures. It is routed through a pressure supply panel to the calibration chamber and module by way of a Mensor PCS 400 pressure controller and a Pressure Systems Inc. 8400 system. The supply panel consists of a 160-psi TESCO gas regulator, a 150-psi relief valve and a manually operated valve. Gas flows through the regulator, relief valve and the manual valve before exiting through a one meter long, one-fourth diameter inch stainless steel tube. A T-fitting at the end of this tube, simultaneously directs gas to the 8400 system and the PCS 400. The Mensor PCS 400 controls the helium gas to the pressure chamber while the 8400 system controls the helium gas used for calibration pressures to the module.

Data Acquisition System

The Pressure Systems, Inc. 8400 system along with a desktop personal computer is also used for data acquisition. The 8400 system, a commercially available, highly modular analog-to-digital data acquisition system, is a parallel processing system for high speed pressure and frequency scanning up to 200,000 measurements per second. The system consists mainly of a Pressure Calibrate Unit (PCU), and a Scanner Digitizer unit (SDU) that operate together under the control of the System Processor (SP).

The SP, the heart of the system, provides all control and data reduction functions for the 8400 system. It contains a 32-bit microprocessor, a VME Bus, and comprehensive firmware which provides for a high-speed environment. The PCU is a digitally controlled, pneumatic calibration source and pressure generator. Accurate pressure measurement is achieved using the PCU's pressure transfer standard. The SDU, a high speed (50 kHz), 16 bit digital converter, reads transducer voltages from the ESP module. The interface of the ESP module to the 8400 System is accomplished using a Scanner Junction Unit (SJU). Various functions of the 8400 System are controlled from the computer by high language commands written in Microsoft compiled in QuickBasic. The host computer, linked to the SP, specifies the calibration

pressures to be set on the PCU, issues the command, while the SDU reads the transducer voltages at each pressure.

MEASUREMENT PROTOCOL

Measurements are taken at each of three reference pressures and ten or eleven temperatures. Reference pressure conditions are 1, 3, and 8 atm, while temperature conditions may be set from 75, 50, 25, 0, -25, -50, -75, -100, -125, -150 and -175 degrees Celsius (C). Lower and upper temperature readings are set depending on tunnel requests. A calibration at a given reference pressure and temperature is called a “nodal point”. For example, for 3 reference pressures and 10 temperature settings, there are a total of 30 unique nodal points. At each nodal point, differential calibration pressures, with user specified steps (controlled by the PSI 8400 system), are applied to the module over two complete full-scale cycles. The range of differential pressures applied corresponds to the total pressure range of the module. At each step in differential pressure applied on each port, an output voltage (V_p) and temperature voltage (V_{td}) are obtained.

CALIBRATION PROCEDURE

A detailed description of the calibration procedure for the wide temperature modules can be found in reference 4. LMS-TD-0625, the documented task description for this procedure for module M4, can be found in Langley Management System’s Documentation Library under the Aerodynamics, Aerothermodynamics and Acoustics Competency, <http://lms-p/>. In addition to equipment needed, this task description gives the step- by- step procedures for scanner installation, equipment setup, and calibration procedure. Acceptance criteria and how to record calibration data is also documented. After stabilization of the temperature, it takes approximately 1½ hours to complete a calibration run for the three reference pressures at one temperature setting.

Calibration data, in the form of raw data, is loaded on floppy discs and is transferred to a location on the C drive of another computer used for evaluation. This transferred data is first rearranged to a form that is easier to paste into the data analysis template using a spreadsheet program (MS Excel). Sensor coefficients are then calculated, evaluated and finally exported to files to be used by NTF. These

calibration coefficients are downloaded into NTF's software permitting real-time output in engineering units.

DATA EVALUATION

In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of the estimate. Therefore, uncertainty analysis must accompany the coefficients derived from the calibration of the wide temperature modules.

The uncertainty analysis is conducted at each nodal point for each port of the wide temperature module. This includes an analysis of non-repeatability, hysteresis, and static error of the module bridge voltages. The contribution of all three is the total uncertainty. Before analysis is conducted, however, each bridge output, V_p , must be corrected to a common temperature based on the temperature voltage V_{rtd} . This new bridge voltage, V_{pc} , corrects for the interaction between pressure and temperature.

At a given step pressure and nodal point, repeated measurements are taken. This can vary between two and six repeated measurements, depending on the calibration step pressure. Each grouping, which represents a specific calibration step pressure and nodal point, is distinguished by a linear fit. The equation used is as follows:

$$V_p / V_{p0} - 1 = S(V_{rtd0} - V_{rtd})$$

where V_p and V_{rtd} are the measured bridge voltage and temperature voltage measurements, respectively. V_{p0} and V_{rtd0} are the first measured bridge voltage and temperature voltage measurement of the group. S is the fitted slope.

Once S has been determined, corrected bridge voltage, V_{pc} , for the given step pressure at a nodal point is found by the equation:

$$V_{pc} = V_p / [1 - S(V_{rtd0} - V_{rtd})]$$

An average of all V_{pc} 's for a calibration step pressure group is used for all uncertainty calculations and the determination of pressure calibration coefficients. Typically, the correction removes the linear variation of V_p with temperatures as seen in Figure 3.

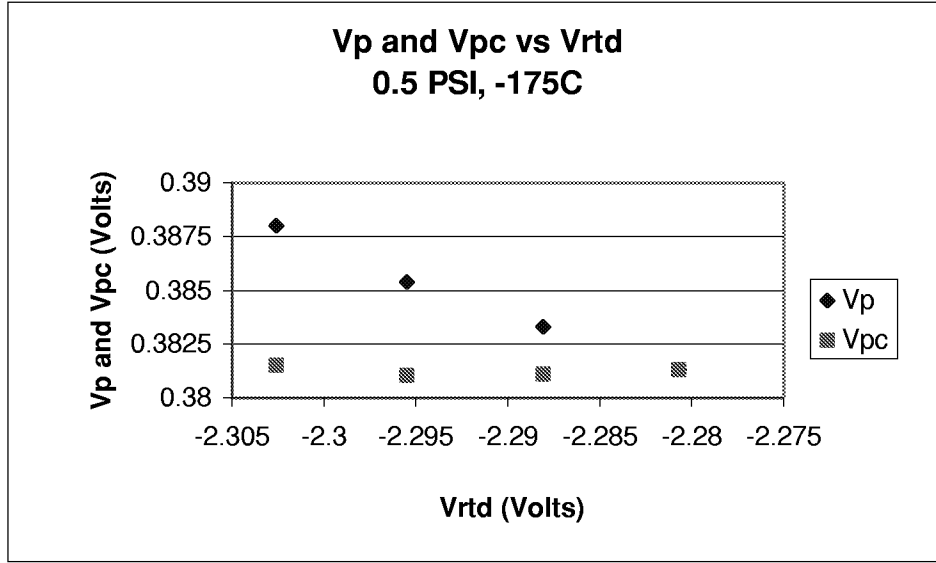


Figure 3. V_p and V_{pc} for Sensor 10 at a Calibration Step Pressure of 0.5 psid, Temperature of -175 °C, and Reference Pressure of 8 atm

Non-Repeatability

Non-repeatability is a measure of the module's inability to reproduce readings under equivalent conditions, consecutively applied. Readings are made at points along the same measurement direction, either increasing from zero or decreasing from full scale. Percent non-repeatability is found as follows:

$$\% \text{ Non - repeatability} = \frac{100[(V_{\text{output}})_{\text{upward first run}} - (V_{\text{output}})_{\text{upward second run}}]}{\text{F.S.O.}}$$

where F.S.O. is the full-scale output expressed in volts. The mean over all differential pressures at a nodal point, excluding zero differential pressure data, is computed to be the non-repeatability.

Hysteresis

Hysteresis is the maximum difference between output readings under equivalent conditions at points along different directions of the measurement cycle. This is found as follows:

$$\% \text{ Hysteresis} = \frac{100[(V_{\text{output}})_{\text{upward first run}} - (V_{\text{output}})_{\text{downward second run}}]}{\text{F.S.O.}}$$

The mean over all differential pressures at a nodal point, excluding zero differential pressure data, is computed to be the hysteresis.

Static Error

Static error is defined as the root-mean-square deviation of fitted from actual measurement data. In this case, corrected bridge voltage, V_{pc} , is fitted to measured differential pressure, P . A fourth order polynomial results from a least-squares fit and is given by the equation:

$$V_{PC} - V_0 = a_1P + a_2P^2 + a_3P^3 + a_4P^4$$

V_0 is the offset voltage, which is constant for a given nodal point. Two sets of coefficients for a_1 , a_2 , a_3 , and a_4 are found for positive and negative P . These coefficients, along with the offset, are used to find fitted voltage, V_{fit} . Percent static error is found from the equation:

$$\% \text{Static Error} = \frac{100 \times \frac{1}{N} \left[\sum_N (V_{PC} - V_{fit})^2 \right]^{1/2}}{\text{F.S.O.}}$$

where N is the number of measurements at the nodal point. The mean over all the differential pressures at a nodal point, excluding zero differential pressure data, is computed to be the static error.

Total Uncertainty

Total uncertainty is the square root of the sum of the squares of the non-repeatability, , and the static error. It is found by the equation:

$$\%Un = (N^2 + H^2 + S^2)^{1/2}$$

where N is the non-repeatability, H is the hysteresis, and S is the static error.

CALIBRATION EXAMPLE

Calibration data were obtained in the NTF Simulation Laboratory for module M4 that has 16 ports and a pressure range of ± 4 psid. Data were taken with this module over a pressure range from +2.5 to -2.5 psid in 2 psid steps, and at 10 temperatures from 50° to -170° C in 25-degree steps. Figure 4 shows a

typical variation in offset voltage for a pressure port on module M4. On average, a variation in offset voltage of 0.3 V is exhibited over the full temperature range for a given pressure sensor. This behavior is evident at all three reference pressure (1, 3, and 8atm) nodal points. Figure 5 presents the typical response, in output voltage, of a single pressure sensor. Over the full pressure range from +2.5 to -2.5 psid, output voltage generally varies about 3 V.

The magnitudes of the components of measurement uncertainty, including the total uncertainty, do not exceed 0.05% F.S.O., on average, over the entire temperature and calibration pressure range for each port of the module. Uncertainty values for non-repeatability, static error, and hysteresis are comparable in magnitude over the entire temperature range. These are shown in Figures 6, 7, 8, respectively. The total uncertainty of all three components is shown in Figure 9.

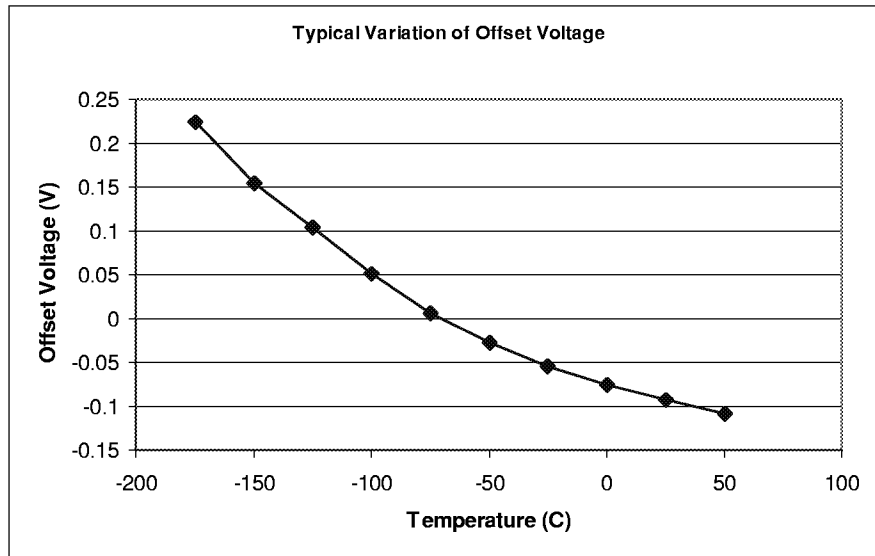


Figure 4. Typical Variation in Offset Voltage for a Single Pressure Port

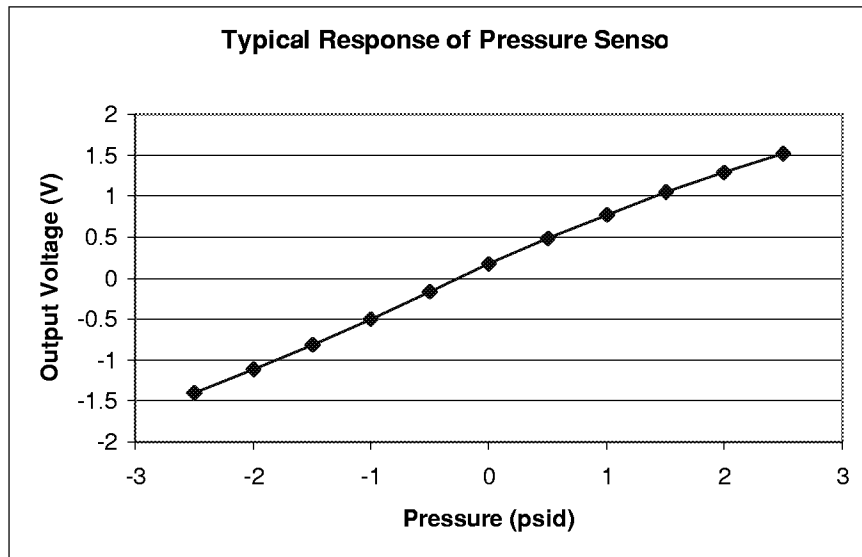


Figure 5. Typical Output Voltage Response for a Single Pressure Port

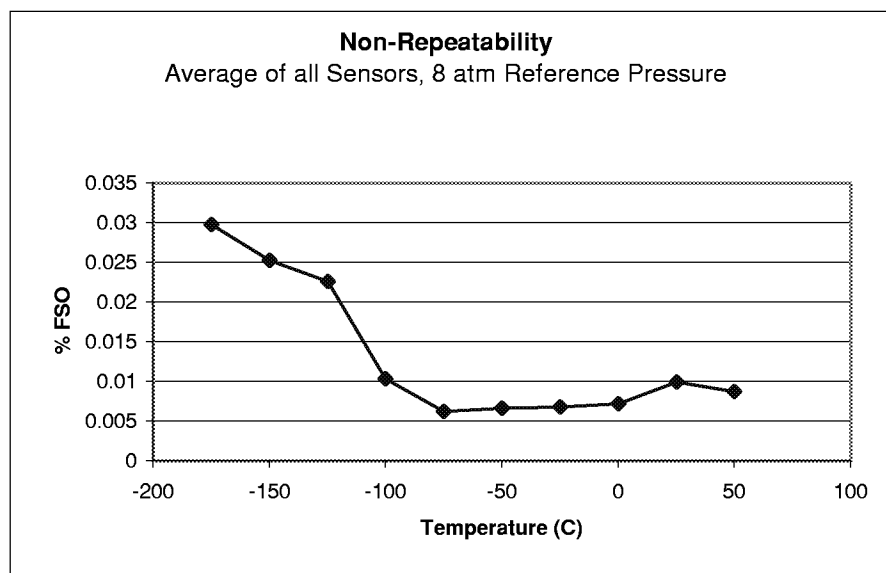


Figure 6. Non-Repeatability expressed in % F.S.O. (Averaged for all Sensors)

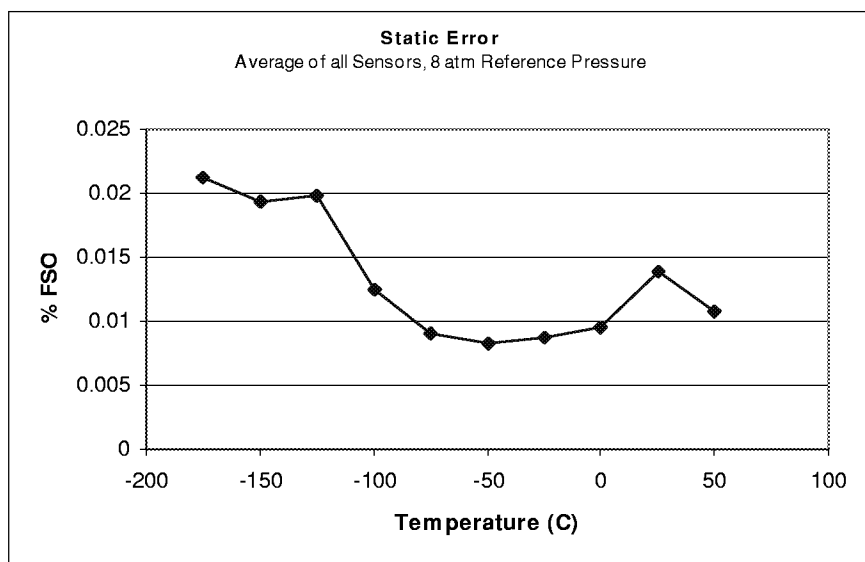


Figure 7. Static Error expressed in % F.S.O. (Averaged for all Sensors)

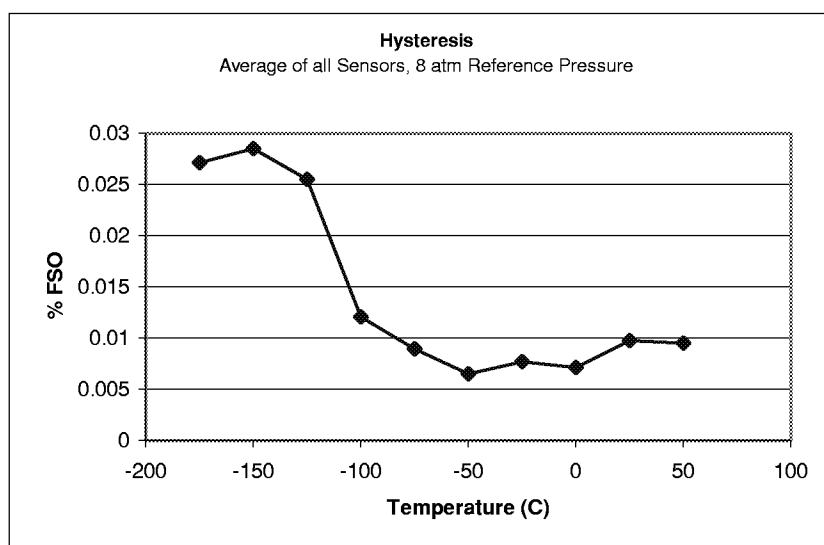


Figure 8. Hysteresis expressed in % F.S.O. (Averaged for all Sensors)

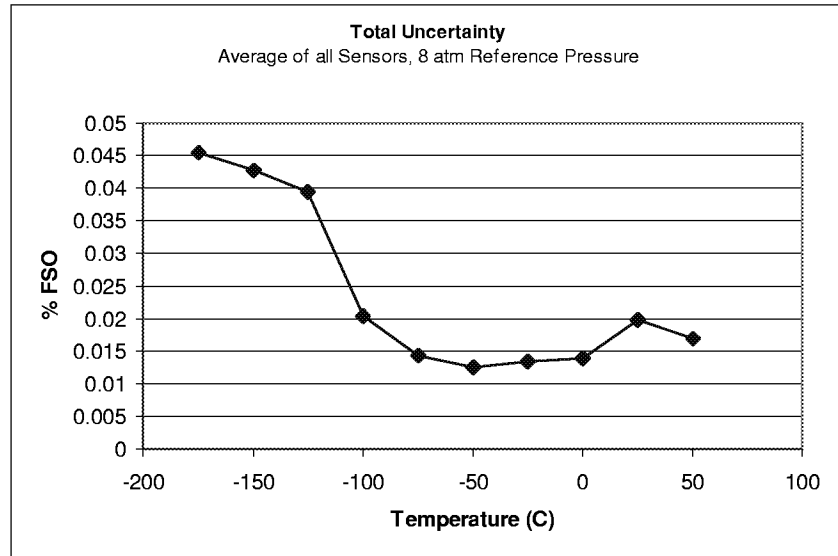


Figure 9. Total Uncertainty expressed in % F.S.O. (Averaged for all Sensors)

CONCLUDING REMARKS

The use of wide temperature modules in wind tunnel tests at cryogenic temperatures eliminates the need to stop tests for re-calibration. To ensure the accuracy of these modules precise and accurate calibration is required. For this purpose, a special laboratory simulating the environmental properties of the National Transonic Facility has been created at Langley Research Center. This laboratory has been tested and clearly meets all the specifications as needed for the calibration of the wide temperature modules. Calibration data can be taken at temperatures as low as -175°C , at 3 reference pressures (1, 3 and 8 atm) and at different pressures depending on the pressure range of the modules. With integrated software, calibration data is taken, calibration coefficients are computed, and evaluation of the data is performed using uncertainty analysis techniques. The calibration coefficients from this laboratory are then submitted to tunnel personnel to be loaded into the tunnel's data acquisition system. Because the wide temperature modules are very stable, this calibration data is estimated to be valid for up to six months.

Future improvements with the system will include full automation of the setting of temperatures and the calibration and reference pressures.

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